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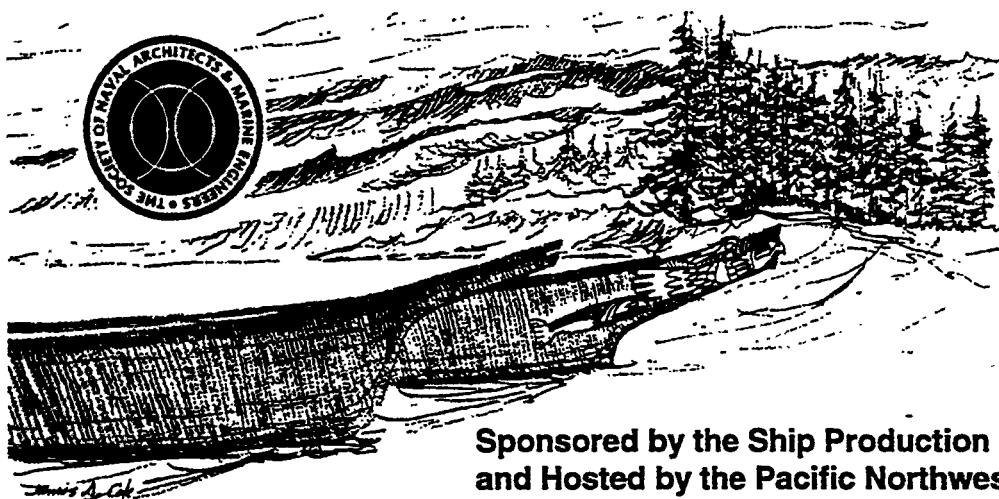
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Shipbuilding Robotics and Economics

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ABSTRACT

Commercial shipbuilding is surviving and prospering in mature high-labor-cost countries even under intense competition from low-labor-cost countries. Prospering shipyards are investing in robotic automation to increase productivity and worker added value. Robot welders are producing higher quality ships for as little as \$1 per hour. It is projected that U.S. shipyards must also use robots in order to successfully compete in commercial world markets. This paper describes how the Technology Reinvestment Project (TRP) on Shipbuilding Robotics is leveraging advanced robotic technology to provide low-cost robotics for U.S. shipyard automation. The TRP is described, economic analysis methods for robot welding are presented, and factors for Successful implementation of robotics are discussed. A case study of a successful shipyard gantry robot implementation is reported.

INTRODUCTION

With the advances in mechanization and automation in manufacturing during the past 40 years, ship manufacturing is also becoming more mechanized. During the past decade a number of shipyards have successfully employed robot welders. Many of these shipyards are welding more than 25% of the ship with robots with goals of over 80%.

A robot welder works for between \$1 and \$5 per hour, produces predictable welds, optimizes weld consumable costs, reduces inspection and rework costs, and delivers a consistent higher quality product. The economics of robot welding

are simple and powerful. Robot welders, working for skilled shipbuilders, make ships better, cheaper, and faster than other methods.

However, present generation shipbuilding robots, known as numerical control (NC) robots, require that shipyard owners have the ability to develop software, hardware, and processes necessary to employ these robots in their shipyard environment.

Identifying a need for a better solution to shipyard automation, the Technology Reinvestment Project's 12 partners, under the leadership of CYBO Robots, are developing a low-cost robot system specifically for shipyards. The project will develop low-cost robot welders designed for the unique needs of U.S. shipyards (Office of the Press Secretary, 1993).

Revitalizing Commercial Shipbuilding in the United States

The geopolitical changes that are reshaping the U.S. defense establishment are having a profound effect on U.S. shipyards. Fewer Navy ships will repurchased as a result of recent changes in world politics that have redirected U.S. defense spending. Projections show that under the status quo, most U.S. shipbuilders will not remain viable during the upcoming periods of low Navy procurement (MARITECH, 1994).

A viable shipbuilding infrastructure is essential to the United States; it is the primary means of building and maintaining the fleet that is the core of modern Naval defense. The only way the United States can afford to retain the shipbuilding capacity necessary for national defense is to assist U.S. shipyards to become

commercially competitive. Otherwise, they will be forced to close, depriving the United States of needed shipbuilding capacity for mobilization, posing a serious threat to national security, and causing even higher Navy ship costs.

This TRP plans to reduce Navy ship costs and to assist U.S. shipyards to become commercially competitive. It anticipates that successful completion of the project will assist shipyards to compete in a \$364 billion world market, increasing the number of high quality jobs in the United States, and help eliminate a national security threat created by U.S. dependence on foreign products in these critical areas (NSA-USRI, 1991) (NSI, 2) 1993).

Competitive Environment

The current competitive environment for world shipbuilding is composed of shipyards with a wide range of labor costs. In industrialized countries, labor costs range from about \$8 to \$23 per hour. Table I details average labor costs for European Economic Community (EEC) and other foreign yards.

Hourly Costs	Country
\$19.60	Belgium, Germany
\$19.05	Japan
\$18.00	Finland
\$17.50	France, Italy, Denmark, Spain, Netherlands
\$8.80	Greece, Portugal, United Kingdom
\$8.35	Korea

Table 1. Hourly Shipyard Costs for European Economic Community and Other Countries (CEC, 1992)¹

WHY ROBOTICS

Much like personal computers increase the abilities of people to manipulate symbols and words in an office, robots increase the abilities of people to perform production processes. Through

¹Labor costs include national social benefit costs.

robotics, the value of human labor is increased, resulting in greater economic return for business and higher wages for workers.

The U.S. is more than 15 years behind Japan and Europe in the application of robots. Japan has at least six to eight times as many robots as the United States, and Japanese companies install more robots each year than the U.S. basin total (RIA, 1993). Robot use in Japan began more than fifteen years ago when Japan began using robots to solve a shortage of skilled workers. They discovered that robots improved product quality and gave them important manufacturing advantages. They also learned that robots: 1) improve working conditions, 2) improve the quality of work, and 3) improve the standard of living for workers, solving societal problems while increasing the value of labor and **justifying higher wage rates.**

During this same period, most U.S. manufacturers had an adequate supply of skilled workers and no fundamental need to employ robots, so they didn't. Only the U.S. automotive sector, faced with a changing market situation created by the improved quality of Japanese automobiles, were forced to adopt robots to achieve the necessary quality and cost-reduction levels.

The Trend to Robotics

Today, the situation for most manufacturing in the United States is changing. Some industries are facing shortages of skilled workers, others have concerns about rising labor costs, and many manufacturers are encountering higher product quality levels established by overseas competitors with robots. In 1992 the U.S. robot industry experienced its first growth in almost a decade. U.S. robot consumption grew to \$590 million in 1992, up from \$415 million in 1989. Continued growth is forecast at about 11% through the end of the decade with 1994 estimated at \$750 million. (Frost & Sullivan, 1994)

In the future, demographic studies predict major shortages of skilled workers as the baby boom generation retires and the need for service workers increases. These shortages will be compounded by declining worker skills and decreasing desirability of manufacturing trades. Further compounding the situation will be the impact of increasing global competition on all

industries, where consumers demand higher quality, more selection, and faster response. All of these factors will increase the need for robots.

Warning Proceed with Caution

During the rush to implement robotics in the automotive industry in the 1980s, many millions of dollars were wasted by moving too fast with too little knowledge. U.S. robotics history contains numerous costly times where foreign robotic technology was seen as a means to catch up. Robotics is a complicated technology with a steep learning curve that is reduced only through knowledge and experience.

Shipyards create a new class of technical issues that must be solved to apply robots. Shipyard robots are different from industrial robots. Industrial robots are designed to work in factories where the environment is structured, organized, precise, and predictable. Industrial robots are designed to perform the same task repeatedly, many thousands of times, and programming can take from days to weeks for each part. Shipyard needs are different. Most ship components are currently manufactured with a precision unacceptable for industrial robot applications, and are produced in low volumes, making programming costs prohibitive.

In Japan, shipyards that use robots have had to develop their own proprietary NC robots and software for offline programming. They have also simplified ship designs and modified their shipyards and manufacturing processes to produce the high-precision structural components which current generation NC robots require.

SHIPBUILDING WITH ROBOTS

Numerical Control (NC) Robots

Japanese NC Robots. In the late 1970s, the Japanese shipbuilders began developing NC robots for shipyard welding. One shipbuilder, Hitachi Zosen, is an advanced developer of robots for shipbuilding. The National Shipbuilding Research Program SP-7 Committee sent a team to Japan in April-December 1991 to investigate this system (Blasko, 1993).

The investigating team reported that these NC robots are used primarily for straight line welds.

They are programmed offline by numerical control, similar to machine tool programming. They have touch sensing and an elementary form of arc seam tracking. Ship component accuracy control is critical to use these robots, and parts are prepared and located within ± 1 millimeter.

In early 1992, robotic welding accounted for more than 20% of this shipyard's welding with a near-term objective of 50%, and a long-term goal of 80% of all welding to be done with robots. This shipyard's philosophy combines cost reduction with elimination of difficult and dangerous work while increasing the productivity of workers. Robotics previewed as an integral part of a total manufacturing philosophy, of which the robot is but one element.

The committee's report concludes that the application of robots provides good potential to improve the competitive position of U.S. shipyards, but that selective picking and choosing individual elements of Japanese shipbuilding technology to be used in U.S. shipyards will have hidden costs because of the need to integrate that equipment with the ship design and construction process planning effort. Selecting individual elements of technology or equipment without developing an integrated system for ship design, process planning, and construction was not advised (Blasko, 1993).

NC Robots in Denmark. Odense Steel Shipyard began automating ship production in 1984 with an ESPRIT project to apply Computer **Integrated Manufacturing (CIM) to heavy welded** fabrication. In 1987, they entered into a license agreement with Hitachi and began incorporating NC robots into their automation.

Since that time they have made a sizable investment in the development of their own proprietary software and hardware to apply these NC robots in their ship production. Their robot systems, offline programming software, welding processes and manufacturing methods are now among the best in the world. They have rationalized and integrated a total shipbuilding factory and improved the efficiency of the application of NC robots. They have also developed proprietary robot handling equipment, programming tools, and process monitoring systems. By 1991 they were producing double hulled tankers with this system, and are currently

expanding and improving its performance. The economic results of an application of their gantry mounted robots are presented in this paper as a case study.

Specialized software was developed by the shipyard to automate the programming of NC robots directly from the CAD ship design data. Their software incorporates rule-based methods to create individual weld path programs from a library of weld process plans. The software also divides the welding tasks for an entire ship panel to create task plans for each welding robot (see Figure 1).

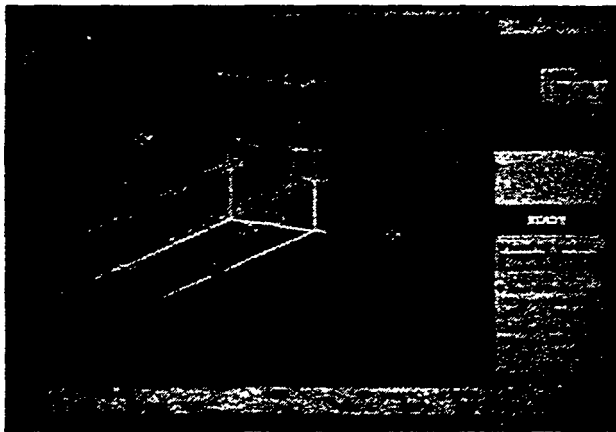


Figure 1. Software for Automatic Programming

These pioneers have demonstrated that NC robot technology can be successfully applied to shipbuilding provided that the production process, the workplace, and the materials are modified to provide a sufficiently structured and controlled environment in which an NC robot can perform its planned tasks. They have also shown that careful planning, creation of a technical development staff, involvement of all shipyard disciplines, and a total shipyard commitment are necessary ingredients for successful implementation of this technology.

Need for U.S. Shipyard Robot Technology

Shipyard robot technology is still in the early stages of development and requires a great deal of technical support by the owner. For example, the Danes invested in equipment and software development for more than 10 years to implement

the Japanese technology. Such custom support is difficult to import due to differences in standard practice, hardware, work methods, communications, and distances between countries. Therefore, local development and support is preferable.

The cost of procuring and implementing foreign equipment and technology is another factor cited as creating the need for a U.S. shipyard robot technology base. Japanese NC shipbuilding robots can cost between \$150,000 to \$200,000 per robot. Support equipment, facility modifications, installation, and training can more than double this cost, making the investment about \$300,000 to \$400,000 per robot. Needed specialized CAD software and robot programming software adds an additional \$1 million to \$2 million of cost. In addition, the shipyard must hire a specialized development staff to design and build the necessary custom equipment, integrate these robots, and develop the necessary support software to integrate their CAD data with the robot programming software. **The Danes, for example, maintain a staff of 20, at an estimated cost of about \$1 million per year, for development and support of their Japanese NC robots.**

For a U.S. shipyard to implement foreign shipyard robots, it is estimated that a minimum investment of between \$3 million and \$4 million is required to begin, and total investment of \$10 million to \$25 million should be expected. The TRP partners felt that most U.S. shipyards lacked the necessary capital to invest in foreign robotics in addition to the necessary investments in new ship designs (NSI, 1993).

Additional factors creating a need for a U.S. shipbuilding robot technology base were the need **for a competitive advantage in shipbuilding. If the U.S. is able to develop a technological lead in shipbuilding robotics, it can use that lead to improve its competitive position and reduce its dependence on foreign technology for national defense.**

TRP Program Goals

The goals defined in the TRP Shipbuilding Robotics include development of: 1) a total robotic welding system for shipbuilding 2) modular robots with advanced sensing and adaptive abilities that

can operate in unstructured environments and be reconfigured for various tasks, 3) a system with user-friendly interfaces acceptable to U.S. shipyard workers unfamiliar with robotics and automation 4) a modular networked system based on open architecture PC-based controls, 5) automatic offline programming that interfaces with various shipyard CAD/CAM design systems, and 6) low-cost support equipment to integrate and transport the robots in the shipyard environment.

The project also has long-term goals to develop 1) real-time weld process quality monitoring 2) adaptive correction of weld problems as they occur, and 3) process control which correlates and records weld quality information with ship location. The planned result will be improved weld quality and reduced cost of weld inspection which should further reduce ship production costs.

NEW GENERATION OF ROBOTS

The planned system includes the following modular components that link together in a variety of configuration 1) modular robots, 2) open-architecture robot controllers, 3) supervisory controllers, 4) offline design and process database system, 5) low-cost part registration systems, 6) Nation low-cost robot positioning devices, 7) sensor-based adaptive process control, and 8) weld quality sensors. Each component of the system will run on low-cost PC hardware and will be linked via standard Ethernet local area networks (LAN).

To reduce costly programming the project is developing offline automatic programming software that uses CAD data to program robot paths in conjunction with knowledge-base system data for weld process and sensors. This automatic programming will work in conjunction with inputs from registration systems to accommodate rough robot positioning and with local robot sensors to adjust these programs to adaptively compensate for variations in component parts.

To ensure that the system design correctly anticipates the needs, and preferences of U.S. shipyards, three major shipyards are members of the development team: Ingalls Shipbuilding, Inc., Bath Iron Works Corporation, and National Steel and Shipbuilding Company. These shipyards are

supplying their welding and manufacturing expertise to assist in developing system specifications to monitor the program, and to test and evaluate the systems and components as they are developed.

The core technology for this project already exists. The commercial, university, and government members of the team are modifying their existing software and equipment to meet the development specifications. Software is being ported to the PC environment, capabilities are being added to enable the equipment to work together, and features are being added to provide the performance and user interfaces defined by the shipyards.

The system operating architecture is being designed to comply with the Next Generation Controller (NGC) Open System Architecture Standard (SOSAS) (NCMS, 1994) and the Unified Telerobotic Architecture Project (UTAP) application architecture (Lumia, 1994). A special meeting of groups concerned with these specifications was held July 25-27 in Atlanta, Georgia, to discuss the planned system. The groups represented included the Navy, the Air Force Material Command (AFMC) Robotics and Automation Center of Excellence (RACE), National Institute of Standards and Technology (NIST), Army Tank and Automotive Command (TACOM), Department of Energy (DOE) Sandia National Laboratory and Oak Ridge National Laboratory, Next Generation Controller (NGC) National Center for Manufacturing Science (NCMS), Boeing, CYBO Robots, and Trellis Software and Controls. At that meeting it was agreed that: 1) the UTAP conforms to and is an application architecture of the NGC SOSAS; 2) the TRP is an implementation of the UTAP Application Architecture and is consistent with the NGC; and (3) Nomad^{TM2} is a specific implementation of the UTAP Application Architecture that provides an execution environment consistent with the NGC. Figure 2 illustrates the relationships of these items (Stoddard, 1994).

²NOMAD is an open-architecture controller product of Trellis Software & Controls, Inc.

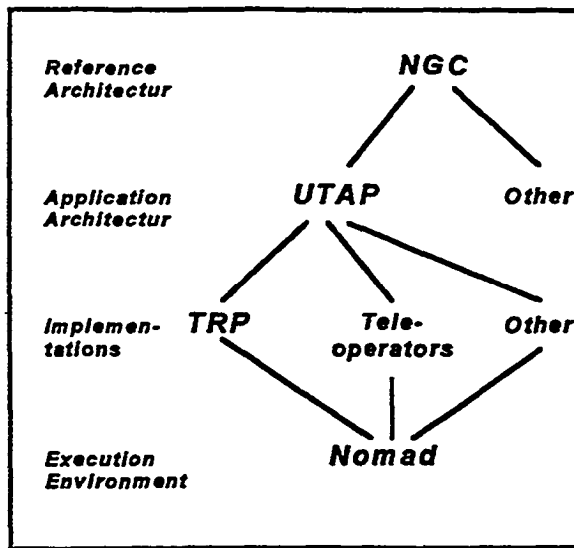


Figure 2. TRP Implementation of the NGC and UTAP

In Phase I of the program, the equipment, software, and systems are being designed, built, tested, and demonstrated. In Phase II, the systems will be installed in shipyards to validate the benefits of robotics in a production environment, refine the system software, and ensure the quality of the system implementation. Phase I is scheduled for completion in June 1996.

Automatic Programming.

The offline welding simulation and database system developed under the Navy's Programmable Automated Welding System (PAWS) will be the heart of the Offline Programming System (OLP). As a part of this project PAWS is being expanded and enhanced to store Ship part descriptions, programming macros, various process strategies, and additional weld process requirements.

For most users, part data are downloaded directly from a shipyard's computer-aided design (CAD) database. For shipyards which are not CAD based, a macro description language is being added to define the basic components of ship panel assemblies and typical panel component intersections.

A process knowledge-base for ship welding is being developed to store the welding process data, weld sensor data, and robot adaptive control Strategies. These databases are linked to users at

an offline process development station through **programming tools consisting of ship section analysis macros and process fitting macros** that are being developed to simplify and accelerate the offline programming tasks.

Once the ship panel design and process knowledge have been entered into the databases, the offline system will determine which robots should be used to weld specific ship sections and where these robots should be placed to optimally weld each section. The offline system generates robot programs taking into account path trajectory, equipment, and welding factors. The offline system also generates maps of robot placement locations and identifies welds that must be manually completed during the tack welding and fitting operations.

Robot Placement. The plan for panel assembly is to fit and tack weld structural components in their proper locations. The robots will be placed on the panel manually or automatically. The physical map generated by the offline system guides manual robot placement. For automatic placement, the offline system electronically sends robot location information to the placement system controller.

In the case of automated gantry robot placement, the panels are assembled in one of the designated fixture zones within the gantry working area. A system operator confirms the panel part number and confirm through the supervisory controller that the panel is ready for welding. once automatic operation is initiated, the supervisory controller moves the robot gantry to the first welding location. The controller correlates part location registration data from registration sensor systems with offline weld paths to generate and download weld paths to each robot.

A similar procedure is used when robots are placed manually or by crane. In all cases, there is no need to directly program the robot either on line or offline. All programming is automatic from the information stored in the offline database.

Robot Registration. Robot registration is performed prior to weld start to compensate for robot placement and inaccuracies in the preparation and fit-up of the section to be welded. The robot programs contain instructions for registration of the robot position with respect to the section to be

welded. Three types of robot registration are available. One or more registration methods may be used depending upon the precision of the preparation of the sections to be welded, and the precision with which the robot is placed.

A registration system based on triangulation provides the location of the section to be welded and the robot to about ± 25 mm (1 inch). A the dimensional (3-D) sensor mounted on the robot provides registration between the robot and the section to be welded to about ± 7 mm (0.28 inch). Displacement sensing provides registration of the robot to the section to about ± 1 mm (0.04 inch).

Adaptive Capabilities. The robot can work in conjunction with a variety of sensors to achieve adaptive process control. Sensors include optical, touch, arc tracking and vision. Through these systems the robots are able to compensate for variations in robot and part locations and weld joint fit-up. Sensors are provided to locate the precise weld start and stop locations, to adjust process parameters including fill, weave, and position based on fit-up variations, and monitor and control the position of the welding arc with respect to the weld joint center location.

Weld Quality Monitoring. A weld quality monitor will be available for each robot. The sensor collects and analyzes data gathered during welding to determine that weld quality is maintained within established limits. If the welding wire runs out, or welding problems develop due to faulty wire feeding equipment or inadequate weld gas coverage, the affected robot stops and alerts the system operator. The operator can then make corrections and instruct the system to resume from where it stopped.

Upon completion of each weld segment, a weld record database for that section will be updated to record the welds completed, the weld cycle time, and the monitored process quality data. This information can be used for statistical process control (SPC) to determine where manual welders must complete unfinished welds, and to direct weld inspection and repair.

User Friendliness. The functional specifications for the system have been created by surveying the participating shipyards to determine their manufacturing practice and methods. User-friendly interfaces and methods that mirror

common U.S. shipyard practice are designed into the system to tie together the existing shipyard infrastructure in a manner acceptable to shipyard workers, technicians, engineers, and managers.

Maintenance. Maintenance costs for the system will be low. The use of open-architecture, PC-based controllers will greatly reduce maintenance costs. Components are available from a wide range of sources, and the popularity of PC hardware ensures availability of a large body of trained technicians to support the equipment.

ROBOT ECONOMICS

Traditional U.S. financial analysis practice uses different methods to evaluate capital investments depending upon the nature of the investment. For example, an investment in a facility is evaluated over the expected useful life of the facility, including equipment in the case of dedicated facilities like steel mills and chemical plants. A useful life of 30 years might be used for such evaluations. Investment in manufacturing equipment is usually evaluated over shorter periods because equipment is often superseded by new and more efficient models. A useful life of 3 to 5 years is commonly used to evaluate such equipment, with many companies seeking payback of investment in 1 to 3 years. Investment in labor is rarely evaluated. Labor is usually treated as available "on demand," that is, it can be obtained or discharged at will.

A lack of a historical financial analysis practice for robots creates a dilemma for performing robot economic evaluations, whether they should be considered facility, equipment, or labor. Arguments can be made to support each method, as robots have characteristics of all three. Like a facility, robots can be a part of the basic structure of a manufacturing business, are universal, can be applied to many tasks, and can be used by different owners. Like equipment, a robot can be used for specific tasks, but unlike equipment can be upgraded with new processes when they are available. Are robots more like repurchased labor? Like labor robots can be used for many tasks, moved to many locations, and can be taught and re-taught various skills and duties, and if in excess, can be sold.

If a **business** considers robots as integral to the manufacturing process and evaluates robots as a part of a facility investment, the financial analysis will focus on long-term objectives.

If robots are treated as equipment, they must compete against specialized machines that typically are expected to provide quick returns on investment. Such specialized machines generally have limited versatility and can be quickly made obsolete by a change in process or design. Equipment owners generally seek rapid payback of their investment to ensure that prompt equipment replacement can be justified if required to remain competitive. Such an analysis method may eliminate robot solutions and sacrifice long-term strategic advantages for short-term returns.

Robots may be more appropriately considered direct labor replacements. However, at present, the methods for evaluating labor are not investment-based. Typically labor is treated as a service that is purchased at-will and measured on an hourly or annual cost basis. Often only direct labor compensation is considered, without calculating the total social costs, and rarely, if ever, are the projected length of employment and termination costs computed and included in labor cost. Therefore, if robots are to be evaluated as labor alternatives, a new method is needed.

An argument can be made for developing this method as follows. Current manufacturing practice usually relies on a significant amount of skilled and semi-skilled labor. The total amount of labor to be performed is usually known and costs are typically assigned to the labor content. These costs are often based on an hourly labor rate. If one considers the life span of the business as the basis for needing labor, a robot can be reconsidered as an alternative to at-will labor employment. The business can then evaluate the financial impact of a strategic decision to use robot labor versus at-will labor. Following is a quick method to compare robot to labor using hourly costs.

Hourly Robot Cost

The evaluation of robots on an hourly labor cost basis describes the cost savings benefit in terms that permit comparison to manual labor. To compare robots to manual labor, one must first describe their relative efficiencies.

Robot Efficiency

Typically, a manual welder's efficiency is estimated between 15% and 40% arc time depending upon the process and the welding position. The national average arc time is estimated at about 30%, but this figure may be high (Pavone, 1983).

A robot will typically average 60% to 90% arc time depending on the type of work (Pavone, 1983). If we assume the average robot will achieve the average of this range, the robot will have a 75% arc time.

$$(60\% + 90\%)/2 = 75\% \quad (1)$$

Compared to the manual welder's average arc time of 30%, the efficiency of the robot is 2.5 times (2.5x) that of the manual welder.

$$75\% / 30\% = 2.5x \quad (2)$$

In most shipyard applications, the robot cannot work alone. The robot must be serviced by an operator. One operator can keep between 1 and 4 robots supplied with work, for an average of 2.5 robots.

$$4 \text{ robots} / 1 \text{ operator} = 2.5 \text{ robots per operator} \quad (3)$$

Therefore, one operator divided among 2.5 robots consumes 0.4 times relative efficiency.

$$1 \text{ operator} / 2.5 \text{ robots} = 0.4x \quad (4)$$

Therefore, for shipyard applications, one can adjust the relative efficiency calculated above by this factor. Hence:

$$2.5x - 0.4x = 2.1x \quad (5)$$

Figure 3 illustrates how a robot operating at this efficiency can provide output of 2.1 to 6.3 manual welders depending on the number of shifts the robot is employed.

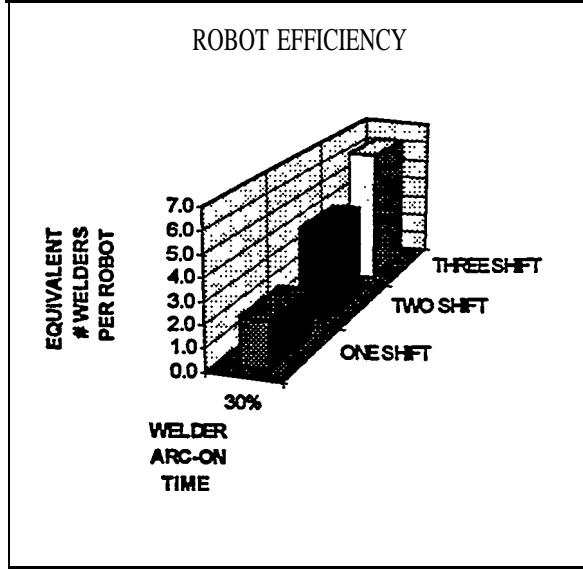


Figure 3. Robot Efficiency

Process Efficiency. Another potential robot efficiency factor is process efficiency. In arc welding a robot can deliver higher deposition rates than manual welders due to its ability to hold a steady arc under the severe environmental conditions of heat, smoke, and light generated by the process. Robot weld deposition rates can range from 20% to 100% higher than manual rates. This provides a direct increase for robot efficiency of 0.2x to 2x.

$$(100\% + 20\%) / 100\% = 0.2x \quad (6)$$

and

$$(100\% + 100\%) / 100\% = 2x \quad (7)$$

Actual process efficiency improvements for shipyard robot welding have not been reported. If we assume them to be about 20%, we can use the efficiency factor of 0.2x (see Equation 6).

Therefore the estimated shipyard robot efficiency factor will be 2.3x.

$$2.1x + 0.2x = 2.3x \text{ (shipyard efficiency)} \quad (8)$$

Robot Hourly Cost. An hourly robot cost can be calculated that describes the cost of the

robot directly compared to the manual labor alternative. This robot cost on a per-hour labor basis can be calculated as follows:

$$(C_R (1 + M_R) + P_R) / (L_R \times E_R) = RC \quad (9)$$

where:

C_R = Initial robot cost (\$)

P_R = Expected programming cost (\$)

M_R = Expected maintenance over robot life in percent of initial cost (%)

L_R = Expected robot life (hours)

E_R = Estimated robot efficiency factor (%)

RC = Robot hourly cost (\$)

Initial robot cost typically varies from \$50,000 to \$200,000 depending upon the manufacturer, size, and features. The new generation robots are projected to cost less than \$50,000, while Japanese NC robots cost between \$150,000 to \$200,000 each.

Programming costs vary widely depending upon the specific robot application. For example, in a high-volume production situation where the same tasks is performed throughout the life of the robot, programming costs might be a few thousand dollars. In a shipyard production situation, where the robot is frequently programmed, the **programming costs might range from \$200,000 for teach programming, to as little as \$10,000 for automatic programming, depending upon the number of programs required and the efficiency of the programming method.**

The programming costs for the new generation robots can be calculated by dividing the estimated initial software and hardware costs plus the 5-year software operation costs by the number of robots to be programmed and the 5-year estimated robot life as follows:

$$(\$100,000 \text{ initial cost} + (5 \times \$50,000 \text{ operating costs})) / (25 \text{ robots}) = \$14,000/\text{robot} \quad (10)$$

The programming costs for Japanese NC robots can be calculated similarly:

$$(\$1,000,000 \text{ initial cost} + (5 \times \$50,000 \text{ operating costs})) / (25 \text{ robots}) = \$50,000/\text{robot} \quad (11)$$

Maintenance costs can be expected to be about 50% of the initial cost of the robot, depending upon the robot manufacturer's design, the application, the operating environment, and the maintenance provided.

Robot life is typically 3 shifts per day for 5 years, or about 30,000 hours, without major overhaul depending upon the environment, application, and maintenance.

Robot efficiency factors have been described previously. Therefore, for a new generation shipyard robot the hourly robot cost can be Calculated as:

$$(\$50,000 (1 + 0.5) + \$14,000) / (30,000 \text{ hrs.} \times 2.3) = \$ 1.29 / \text{hour} \quad (12)$$

For Japanese NC robots for shipbuilding the hourly costs for these robots would be:

$$(\$150,000 (1 + 0.5) + \$50,000) / (30,000 \times 2.3) = \$3.98 \text{ per hour} \quad (13)$$

and,

$$(\$200,000 (1 + 0.5) + \$50,000) / (30,000 \times 2.3) = \$5.07 \text{ per hour} \quad (14)$$

respectively.

By this method, it can be calculated that, over a large range of initial robot costs, assuming a 50% cost for lifetime maintenance. and a 25% cost for

between \$0.73 and \$5.83 per hour as shown in Figure 4.

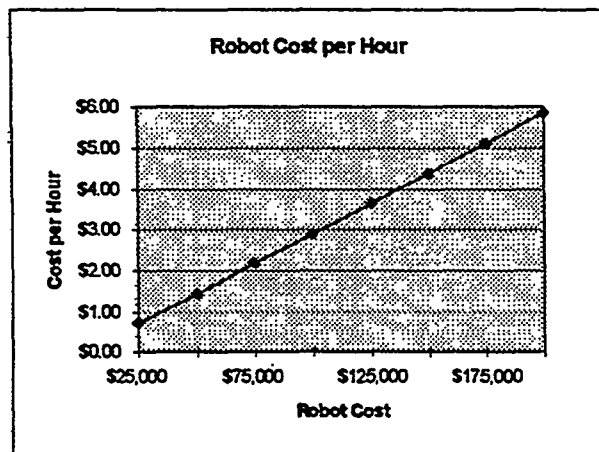


Figure 4. Robot Cost per Hour

Period Cost Savings Method

To extend the output of the above hourly cost method to calculate period cost savings the following steps can be taken.

$$LC - RC = S \quad (15)$$

and,

$$\text{number of robots} \times Sh \times Y \times H = \text{Total Savings} \quad (16)$$

where:

S = Savings (\$)

RC = Robot hourly cost (\$)

LC = Labor hourly cost (\$/hr)

Y = Years

Sh = Shifts

H = Hours worked per shift-year

For example, if a shipyard with a \$20 per hour labor rate evaluates producing 3 shifts per day with 50 robots for the next 5 years, the following savings can be calculated for the \$50,000 robots:

$$\$20.00 - \$1.26 = \$18.71 \text{ per hour} \quad (17)$$

yielding:

$$50 \times \$18.71 \times 3 \times 5 \times 1920 = \$26,942,400 \quad (18)$$

in total savings.

For the \$150,000 robots:

$$\$20.00 - \$3.98 = \$16.02 \text{ per hour} \quad (19)$$

yielding:

$$50 \times \$16.02 \times 3 \times 5 \times 1920 = \$23,068,800 \quad (20)$$

in total savings.

Direct costs savings of this magnitude are significant. It is estimated that robotic welding will yield additional savings in inspection, rework, and consumables that will more than equal these direct labor costs. If this is true, savings of over \$50 million could be anticipated in the above example.

Additional Factors

In the preceding calculations a manual welder efficiency of 30% arc time was assumed. This arc time is very aggressive, with some shipyards

reporting actual arc times between 15% and 20%. If the actual shipyard manual welding efficiency is different than the 30% used, the results of the calculations will differ significantly. Figure 5 shows how variations in manual welder are-on time impact the relative calculations of robot savings.

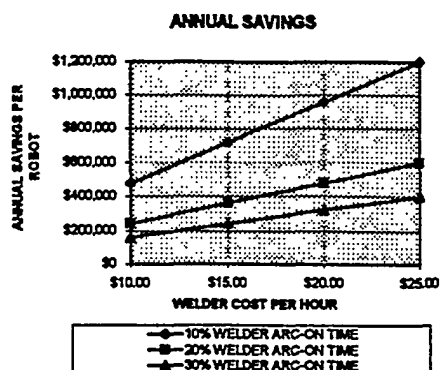


Figure 5 Annual Savings

CASE STUDY - GANTRY ROBOTS

A Danish shipyard produces various types of vessels, ranging from supply vessels to super tankers in the Very Large Crude Carrier (VLCC) Class (Skjolstrup, February 1994). Throughput is important to this yard's operation; each production department completes its work on a ship in 60 days, and a ship leaves the shipyard in 10 months. Robot welders produce consistent high quality welds as pictured in Figure 6.



Figure 6. Close-Up of Robot Weld

The yard currently has 26 robots in production that are used in both block assembly and in sub-element fabrication for blocks. Four methods move and position robots for welding double hulled tankers: 1) manual relocation 2) gantry positioning 3) master-slave gantry positioning and 4) telescoping boom system for double hulled tankers. The manual relocation robots are pictured in Figure 7.

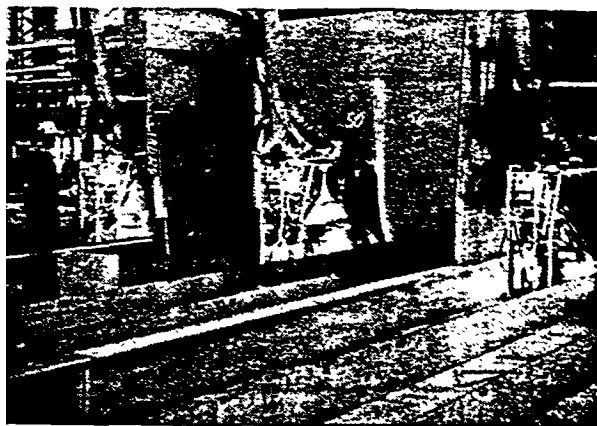


Figure 7. Manual Relocation Robots

Gantry Robot Application. In the gantry robot application pictured in Figure 8, there are four independent gantries mounted on one rail system. **Each gantry has three servo-controlled axes** to position the robots over the sub-elements to be welded. The track is 68 meters long and up to two gantry robots can work on the same sub-element at the same time. The shipyard reports that the one robot-per-gantry system is very flexible and it is easy for one operator to handle multiple gantries. The objective of this analysis is to compare robot efficiency with manual welding efficiency.



Figure 8 Two Gantry Robots

Manual welding speed and robot welding speed differ due to the more efficient process delivery capabilities of the robot. Table II lists average welding speeds for both types of welding.

Weld Position	Manual Welder	Robot Welder
Vertical up	100 mm/ min	150 mm/ min
Downhand	250 mm/ min	400 mm/ min

Table II Welding Speed

Manual Welding Efficiency. Manual welders range between 10% and 40% arc time. Typically they average between 20% to 30% arc time. The work day consists of 14.4 productive hours on two shifts. Of this, 1.4 hours are used in repair, netting 13 hours of welding each day, or 6.5 hours per shift per welder. For ship sub-elements, 20% of the welding is vertical up and 80% is downhand, yielding an average manual weld speed of 220 mm/minute. Therefore, a person with an arc time between 20% and 30% produces between 16 and 24 m/day of weld.

Gantry Robot Welding Efficiency. The gantry robot department produces about 370 sub-elements per ship. With 233 work days available per year and 60 days per ship, this yields 1440 total sub-elements per year. The average weld length per sub-element is about 100 meters; therefore, the average weld length produced per day is:

$$(1440 \text{ subs} \times 100 \text{ m weld/ sub}) / 233 \text{ days} = 618 \text{ In/day} \quad (17)$$

As there are four robots, this yields:

$$618 \text{ m/day} / 4 \text{ robots} = \sim 155 \text{ m/robot/day} \quad (18)$$

which is equivalent to between 6 and 9 manual welders per robot.

Future Efficiency Improvements. The factors that affect system efficiency are robot availability, material availability, and data availability. One way to measure total system performance is to calculate arc-on time. For this gantry system the average weld speed for robot welding of sub-elements is 350 mm/min. Therefore the average arc-on time for each robot is:

$$(155\text{m}/350 \text{ mm/min}) / (14.4 \text{ hours/day}^3 \times 60 \text{ min/hr}) = 52\% \text{ arc time.}$$

Due to work schedule rules (required breaks) for this facility, this calculated arc time must be **adjusted to obtain true arc time. The adjustment factor is 0.8**, therefore the effective arc time is:

$$52\% / 0.8 = 65\% \text{ arc time}$$

The current goal is to increase effective arc time to 75%, and the shipyard automation team believes that 82% arc time is possible. When this level of efficiency is achieved, the robots will be producing at the equivalent rate of 5 to 7.5 manual welders per shift.

To achieve these levels, improvements in operator efficiency and machine availability must be made. The 65% arc time represents 75% of the actual run time. The remaining 25% is used for robot positioning, sensing, calibration, and safety. For this system the gantry run time is 87% of the total time, with 13% of the time used for consumables, handling, and set-up. This can be expressed as follows:

³This particular shipyard's work rules create a situation where the robots work 14.4 hours per day. Robot, in general, are capable of working 24 hours per day.

$$\text{Arc Time \%} = \text{Operator Efficiency} \times \text{Machine Availability} \times \text{Process Efficiency} \quad (19)$$

Currently the shipyard is achieving:

$$52\% = 80\% \times 87\% \times 75\% \quad (20)$$

In the near term the goal is to improve operator efficiency to 90%, and machine availability to 97% such that

$$75\% = 90\% \times 97\% \times 85\% \quad (21)$$

The long-term goal is to improve operator efficiency to 100% which will result in an arc time of 820%:

$$82\% = 100\% \times 97\% \times 85\% \quad (22)$$

Weld Wire Deposition Rates. In terms of weld wire deposited the following estimates were reported:

Source	Kg of Weld wire deposited
Odense Shipyard - '93	4,200 Kg/ robot/ yr
Best Japanese shipyard - '93	3,300 Kg/ robot/ yr
Other Japanese shipyards	2,500 Kg/ robot/ yr
Odense target	15,000 Kg/ robot/ yr
Japanese target	10,000 Kg/robot/yr

Table III Deposition Rates

Conclusions. Gantry robots in production for more than a year have demonstrated sustained production efficiencies as forecast. It is further believed that these efficiencies can be significantly increased by improvements in system operation elements increase the available arc time of the robots.

CONCLUSIONS

Automation is a process, not an event. It consists of many individual steps that are performed and improved over time to achieve

improved quality and efficiency. The following guidelines are offered to assist those considering investment in automation.

Design for Automation. Automation is a total manufacturing philosophy. It begins with ship design, incorporates manufacturing methods, and (20) requires total involvement of material procurement and preparation. Therefore, as new ships are designed, robotic automation should be an integral ingredient of the design process. Today, however, most ship designers have little or no experience with robots. Shipyards embarking on an automation path must look to robot suppliers and others for assistance during the design process.

Part Precision Requirements. NC shipbuilding robot technology requires that robots be presented to a workpiece in a precise and controlled manner, and that the workpiece be precisely prepared for the robot. Typical part preparation precision tolerances for NC robot welding are +/- 1 to 3 mm. (0.04 to 0.12 in.). The new generation shipyard robots under development will be capable of compensating for variations in part location of +/- 150 mm (6 inches), and detecting variations in part fit-up of +/-5 to 6 mm (0.2 to 0.24 in.), with real-time weld compensation depending upon the process, material thickness, joint type, and defect type.

Precision preparation of ship components requires investment in equipment and methods. Shipyards using NC robot technology must purchase part preparation equipment capable of **preparing parts to at least +/- 1 to 2 mm (0.04 to 0.08 in.)**. The new generation shipyard robots will be able to compensate for larger part variations, but better precision is recommended as it will yield higher productivity and quality.

Operating Requirements. NC shipbuilding robots operate in enclosed factories. They are not capable of outdoor production and operation in damp or high dew point environments. The new generation robots will be capable of working outdoors in damp environment.

Worker Skills. NC shipbuilding robots require a staff of highly skilled technicians to install, operate, and maintain the robots and systems. Lower skilled workers can be used to tend the robots, but skilled welders will be needed to make weld repairs. The new generation robots will

require less supervision and will make higher quality welds requiring fewer repairs, thus reducing the number of skilled and semi-skilled workers.

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